



**Faculty of Mechanical Engineering**

**LOW FREQUENCY FRICTION INDUCED VIBRATION OF  
AUTOMOTIVE DISC BRAKE**

**Kumaresan A/L Magaswaran**

**Master of Science in Mechanical Engineering**

**2014**

**LOW FREQUENCY FRICTION INDUCED VIBRATION OF AUTOMOTIVE DISC  
BRAKE**

**KUMARESAN A/L MAGASWARAN**

**A thesis submitted  
in fulfillment of the requirements for the degree of Master of Science in  
Mechanical Engineering**


**Faculty of Mechanical Engineering**

**UNIVERSITI TEKNIKAL MALAYSIA MELAKA**

**2014**

## DECLARATION

I declare that this thesis entitle “Low Frequency Friction Induced Vibration of Automotive Disc Brake” is the result of my own research except as cited in the references. This thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.


Signature :  .....

Name : KUMARESAN A/L MAGASWARAN

Date : 08/09/2014 .....

## APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Mechanical Engineering

Signature :   
Supervisor Name : Dr. Muhammad Zahir  
Date : 08 Sep'14

## **DEDICATION**

To my beloved mother, father, friends, lecturers and God

## ABSTRACT

The automotive disc brake low frequency vibration has been a major concern in warranty issues and a challenging problem for many years. A variety of tools have been developed which include both experimental studies and numerical modeling technique to tackle the problem. The aim of this project is to develop a validated mathematical model considering the dynamic friction characteristics in the vibration of the disc brake. A key issue in the process is to investigate the structural deformation of the brake due to the friction distribution at the pad and disc contact during a typical braking cycle. A new methodology is introduced whereby the Green's equation is utilized to deduce the motion of the brake pad during braking. An experimental investigation using a brake dynamometer is also carried out to measure the vibration characteristics which are then used to validate the results predicted by the mathematical modeling. It is demonstrated that the mathematical model enhances the understanding of the time dependent non-linear contact behavior at the friction interface. The model was able to correspond to the frequencies of each modes obtained from the experiment with an average of 5 %. This, model in turn, demonstrated the fugitive nature of brake pad oscillation that appears and disappears as a function of friction distribution throughout the braking period. Parametric studies on the pressure and speed effects determine the contribution of each of these factors to brake pad leading end and trailing end behavior. The effects of these parameters were found to be modal depend, the decrease in speed during braking gave rise to vibration at frequencies between 500 Hz to 700 Hz where else braking at higher pressures subdued the vibration frequencies between 650 Hz to 850 Hz. Thus this approach can be used as a study tool to evaluate disc brake low frequency vibration using the mathematical model.

## ABSTRAK

*Getaran frekuensi rendah cakera brek automotif telah menjadi kebimbangan utama dalam isu-isu jaminan dan masalah yang mencabar untuk beberapa tahun. Pelbagai alat telah ditubuhkan yang merangkumi kedua-dua kajian eksperimen dan teknik pemodelan berangka untuk menangani masalah tersebut. Tujuan projek ini adalah untuk membangunkan satu model matematik disahkan mempertimbangkan ciri-ciri geseran dinamik dalam getaran brek cakera. Isu utama dalam proses ini adalah untuk menyiasat ubah bentuk struktur brek disebabkan oleh pengagihan geseran pada pad dan kenalan cakera semasa kitaran brek biasa. Satu metodologi baru diperkenalkan di mana persamaan Green digunakan untuk menyimpulkan gerakan pad brek semasa membrek. Siasatan ujikaji menggunakan dinamometer brek juga dilakukan untuk mengukur ciri-ciri getaran yang kemudiannya digunakan untuk mengesahkan keputusan yang diramalkan oleh model matematik. Ia menunjukkan bahawa model matematik meningkatkan pemahaman kali bergantung tingkah laku sentuhan bukan linear pada antara muka geseran. Model ini dapat sesuai dengan kekerapan setiap mod pandangan yang diperolehi daripada satu eksperimen ini dengan purata sebanyak 5%. Ini, model pula menunjukkan ciri semulajadi buruan brek pad ayunan yang muncul dan hilang sebagai fungsi pengedaran geseran sepanjang tempoh brek. Kajian parametrik pada tekanan dan kelajuan kesan menentukan sumbangan setiap faktor-faktor ini berakhir terkemuka pad brek dan ketinggalan tingkah laku akhir. Kesan parameter ini telah didapati ragaman bergantung, penurunan dalam kelajuan semasa membrek menimbulkan getaran pada frekuensi antara 500 Hz 700 Hz mana lagi brek pada tekanan yang lebih tinggi rendah frekuensi getaran antara 650 Hz untuk 850 Hz. Oleh itu pendekatan ini boleh digunakan sebagai alat kajian untuk menilai cakera brek getaran frekuensi rendah menggunakan model matematik.*

## **ACKNOWLEDGEMENTS**

First and foremost, my deepest grateful and thanks goes to my parents, my dear siblings, my dear friends. Their continuous prays and moral supports have been brought me here.

I would like to express my sincerest gratitude to my main supervisor, Dr. Muhammad Zahir Bin Hassan for his guidance, support, and constant encouragement during my research.

I would like take this opportunity to thank my colleagues at the Faculty of Mechanical Engineering, UTeM, for their outstanding collaboration in the experimental works and also for being a very good sharing partner during my research and for providing me an enjoyable study environment.

Finally, I also gratefully acknowledge Universiti Teknikal Malaysia Melaka (UTeM) and the Ministry of Higher Education (MOHE) for their financial support via the provided research grant in this research activity.



---

## TABLE OF CONTENTS

	PAGE
DECLARATION	
DEDICATION	
ABSTRACT	i
ABSTRAK	ii
ACKNOWLEDGEMENTS	iii
TABLE OF CONTENTS	iv
LIST OF TABLES	vii
LIST OF FIGURES	ix
LIST OF SYMBOL	xiii
LIST OF ABBREVIATIONS	xv
LIST OF PUBLICATIONS	xiv
 CHAPTER	
1. INTRODUCTION	1
1.1 Introduction	1
1.2 Problem Statement	2
1.3 Objective of research	3
1.3.1 Objective	3
1.3.2 Methodology	4
1.4 Organization of thesis	5
 2. LITERATURE REVIEW	7
2.1 Introductions	7
2.2 The brake system	8
2.2.1 Historical Background	8
2.2.2 Brake Component and Function	10
2.3 Description of automotive disc brake system noise and vibration phenomena	12
2.3.1 The high frequency domain	13
2.3.2 The low frequency domain	13
2.4 Theoretical Approach	14
2.5 Experimental Approach	16
2.6 The Green's Equation	18
2.7 The brake system behavior	18
2.8 Summary	22

<b>3.</b>	<b>METHODOLOGY</b>	<b>24</b>
3.1	Introduction-The need for a new approach	24
3.2	Over all integrated approach	25
3.3	Experimental modal analysis	28
3.4	Experimental work using Brake Dynamometer	29
3.5	Construction of mathematical model	29
3.6	Friction pair contact dynamics studies	30
3.7	Summary	31
<b>4.</b>	<b>EXPERIMENTAL WORK</b>	<b>32</b>
4.1	Introduction	32
4.2	Experimental Modal Analysis	33
4.3	Experimental equipment	34
4.4	Experimental procedure	37
4.5	Results of Experimental Modal Analysis	39
4.7	Experimental Investigation on Brake Vibration Characteristics	45
4.7.1	The Scaling Method	46
4.8	Experimental Apparatus	49
4.8.1	Brake dynamometer	49
4.8.2	Measurement equipment setup	53
4.9	Experimental Procedure	57
4.10	Experimental Results and discussions	57
4.11	Summary	62
<b>5.</b>	<b>MATHEMATICAL MODEL OF BRAKE FRICTION PAIR BY MEANS OF DYNAMIC GREEN EQUATION</b>	<b>63</b>
5.1	Introduction	63
5.2	Disc modeling	65
5.3	Brake pad modeling	73
5.4	Results, Analysis and Discussion	80
5.5	Summary	87
<b>6.</b>	<b>THE STUDY OF BRAKE PAD BEHAVIOR DURING BRAKING</b>	<b>88</b>
6.1	Introductions	88

6.2 Result extraction	90
6.3 Results and discussions	93
6.3.1 Brake pad deformation during braking	94
6.3.2 Friction distribution at brake pad and disc contact during braking	97
6.4 Frequency response of brake pad leading and trailing end	101
6.5 Braking simulation	104
6.6 The brake pad behavior at the leading end	106
6.7 The brake pad behavior at trailing end.	108
6.8 Frequency response of brake pad trailing and leading end due speed and pressure variations	111
6.8.1 Frequency response of brake pad leading and trailing end due to speed variations	111
6.8.2 Frequency response of brake pad leading and trailing end due to pressure variations	115
6.9 Summary	120
<b>7. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK</b>	<b>122</b>
7.1 Conclusion	122
7.2 Recommendations for future research	124
<b>REFERANCE</b>	<b>126</b>

## LIST OF TABLES

<b>TABLE</b>	<b>TITLE</b>	<b>PAGE</b>
4.1	Specification of impact hammer	36
4.2	Specification of accelerometer	36
4.3	Specifications of portable signal analyzer	37
4.4	Frequencies and amplitudes obtained from EMA: Brake Disc	41
4.5	Frequencies and amplitudes obtained from EMA: Brake Pad	43
4.6	List of parameters for translational and rotational kinetic energy calculations	45
4.7	List of parameters for brake pressure calculation	47
4.8	Electric motor specification	48
4.9	List of peak frequency magnitudes of vibration spectrum	58
4.10	Comparison between EMA frequencies and dynamometer experiment frequencies	59
5.1	Disc rotation frequency and its corresponding velocity	66
5.2	Wave number used in simulation	65
5.3	Material and geometric properties of the brake system used to compute mathematical model	77
5.4	Selected arbitrary points for simulation	79
5.5	Comparison between experimental and simulation frequencies	82
6.1	Operating conditions of braking test.(James, 2003)	90



## LIST OF FIGURES

FIGURE	TITLE	PAGE
2.1	Overview of literature review	8
2.2	Brake system components: (Flicker, 2013)	11
2.3	Schematic diagram of forces and moment acting on wheel (Hassan ,2009)	11
3.1	Concept flow chart of research methodology	27
4.1	Overview of Experimental Modal Analysis	33
4.2	Impact hammer (Dytran Instruments, 2007)	35
4.3	Piezoelectric accelerometer ( Dytran instruments, 2007)	35
4.4	Schematic arrangement of experimantal modal analysis	36
4.5	Accelerometer position and impact hammer position on brake pad	38
4.6	Accelerometer position and impact hammer position on brake disc	39
4.7	Excitation of disc from the impact hammer	40
4.8	Frequency Spectrum of brake disc	40
4.9	Frequency response function of brake pad EMA	41
4.10	Excitation of pad from the impact hammer	42
4.11	Frequency Spectrum of brake Pad	42
4.12	Frequency response function of brake disc EMA	43

4.13	Overview of experimental work using brake dynamometer	45
4.14	Drivetrain of the dynamometer	50
4.15	Electrical controls of the brake dynamometer	51
4.16	(a) brake module, (b) Dytran accelerometer and (c) LDS Dactron portable analyzer	52
4.17	Schematic of Brake Dynamometer	53
4.18	Various accelerometer positions	53
4.19	Frequency Spectrum obtained from position 1 at 90km/h	54
4.20	Frequency Spectrum obtained from position 2 at 90km/h	55
4.21	Frequency Spectrum obtained from position 3 at 90km/h	55
4.22	Frequency Spectrum obtained from position 4 at 90km/h	56
4.23	Vibration Spectrum at 90 km/h	56
4.24	Vibration Spectrum at 110 km/h	58
4.25	Vibration Spectrum at 120 km/h	58
4.26	Vibration Spectrum at 130 km/h	59
4.27	Comparison between EMA frequencies and dynamometer frequencies	59
5.1	Over view of the mathematical model	64
5.2	Brake disc oscillation for velocity 90 km/h	68
5.3	Brake disc oscillation for velocity 110 km/h	68
5.4	Brake disc oscillation for velocity 120 km/h	69
5.5	Brake disc oscillation for velocity 130 km/h	69
5.6	Frequency spectrum for velocity 90 km/h	70
5.7	Frequency spectrum for velocity 110 km/h	70
5.8	Frequency spectrum for velocity 120 km/h	71
5.9	Frequency spectrum for velocity 130 km/h	71



5.10	Combination of the spectrums of 90 km/h, 110 km/h, 120 km/h and 130 km/h	72
5.11	Schematic view of the friction pair used in modeling	73
5.12	Cross-sectional view of the friction pair.	73
5.13	Simulation results: FFT plot for velocity 90 km/h	81
5.14	Simulation results: FFT plot for velocity 110 km/h	81
5.15	Simulation results: FFT plot for velocity 120 km/h	82
5.16	Simulation results: FFT plot for velocity 130 km/h	82
5.17	Accuracy comparison between simulation and experiment for 90 km/h	85
5.18	Accuracy comparison between simulation and experiment for 110 km/h	85
5.19	Accuracy comparison between simulation and experiment for 120 km/h	86
5.20	Accuracy comparison between simulation and experiment for 120 km/h	86
6.1	Overview of chapter seven	90
6.2	Brake pad's x-coordinates	91
6.3	Relationship between coefficient of friction and brake line pressure	93
6.4	Relationship of brake line pressure and friction force	93
6.5	Brake pad deformation for 90km/h	96
6.6	Brake pad deformation for 100km/h	96
6.7	Brake pad deformation for 120km/h	97
6.8	Friction distribution at 90 km/h	100
6.9	Friction distribution at 100 km/h	100
6.10	Friction distribution at 120 km/h	101
6.11	Stick and slip mechanism of brake pad	102
6.12	Vibration spectrum of brake pad leading end	103
6.13	Vibration spectrum of brake pad trailing end	103



6.14	Overview of brake pad behavior during braking investigation	105
6.15	Brake pad's x-coordinates	106
6.16	Brake pad leading end behavior at 90 km/h	108
6.17	Brake pad leading end behavior at 100 km/h	108
6.18	Brake pad leading end behavior at 120 km/h	109
6.19	Brake pad trailing end behavior at 90 km/h	110
6.20	Brake pad trailing end behavior at 100 km/h	111
6.21	Brake pad trailing end behavior at 120 km/h	111
6.22	Vibration frequencies of brake pad leading end at 90km/h	113
6.23	Vibration frequencies of brake pad leading end at 100 km/h	113
6.24	Vibration frequencies of brake pad leading end at 120 km/h	114
6.25	Vibration frequencies of brake pad trailing end at 90km/h	115
6.26	Vibration frequencies of brake pad trailing end at 100 km/h	115
6.27	Vibration frequencies of brake pad trailing end at 120 km/h	116
6.28	Vibration frequencies of brake pad leading end at pressure P1	117
6.29	Vibration frequencies of brake pad leading end at pressure P2	117
6.30	Vibration frequencies of brake pad leading end at pressure P3	118
6.31	Vibration frequencies of brake pad leading end at pressure P4	118
6.32	Vibration frequencies of brake pad trailing end at pressure P1	119
6.33	Vibration frequencies of brake pad trailing end at pressure P2	120
6.34	Vibration frequencies of brake pad trailing end at pressure P3	120
6.35	Vibration frequencies of brake pad trailing end at pressure P4	121

## LIST OF SYMBOLS

$A_{cs}$	-	Pad cross-section area
$A_p$	-	Piston area,
$F_T$	-	Total force acting on the brake pad
$F_j(\omega)$	-	The excitation (input) in the frequency domain,
$H_{ij}(\omega)$	-	The frequency response function,
$K_G$	-	pad sheer modulus
$X_i(\omega)$	-	The response (output) in the frequency domain.
$c_{ds}$	-	Pad sheer damping coefficient
$c_d$	-	Pad damping coefficient
$k_p$	-	Pad stiffness coefficient
$w_b$	-	Brake pad motion
$x_a$ and $x_b$	-	Points where piston force is applied
$\mu$	-	Brake pad coefficient of friction
$E$	-	Pad young modulus

$G(x, u)$	-	green's equation
$I$	-	Pad moment of inertia
$L$	-	Length of brake pad
$p$	-	Brake pressure
$t$	-	Time
$u$	-	Arbitrary point
$x$	-	Brake pad x-coordinate
$\delta$	-	Delta Dirac function
$\rho$	-	Pad density

## **LIST OF ABBREVIATIONS**

EMA	-	Experimental modal analysis
NVH	-	Noise, vibration and harshness
SAE	-	Society of Automotive Engineers
SM	-	Semi metallic
NAO	-	Non-asbestos organic
FRF	-	Frequency response function
FFT	-	Fast Fourier Transformation
DAQ	-	Data acquisition system
OEM	-	Original equipment manufacturer
FEA	-	Finite element analysis

## LIST OF PUBLICATIONS

### Journals

**Magaswaran, K.**, Phuman Singh, A. S., & Hassan, M. Z., 2012. High Speed Experimental Study of Friction Induced Vibration in Disc Brakes. *Applied Mechanics and Materials*, 229, 747-749.

**Magaswaran, K & Hassan, M. Z.**,2013. A new method in the identification of noise and vibration characteristics of automotive disc brakes in the low frequency domain. *International Journal of Vehicle Noise and Vibration*. (Revised- waiting decision)

**Magaswaran, K & Hassan, M. Z.**,2013. Prediction of brake friction pair vibration in the low frequency domain using theoretical model. *International Journal of Vehicle Systems Modelling and Testing*. (Accepted-in press)

### Technical Paper

**Magaswaran, K.**, Phuman Singh, A., and Hassan, M., 2013. "An Analytical Model to Identify Brake System Vibration within the Low Frequency Domain," *SAE Technical Paper* 2013-01-2033, doi:10.4271/2013-01-2033.

## Conferences

**Kumaresan Magaswaran**, Amrik Singh Phuman Singh and Muhammad Zahir Hassan, 2012. High Speed Experimental Study of Friction Induced Vibration in Disc Brakes *International Conference of Mechanical and Electronics Technology (ICMET 2012)*. 24<sup>th</sup> – 26<sup>th</sup> July. Kuala Lumpur, Malaysia.

**Kumaresan Magaswaran**, Amrik Singh Phuman Singh and Muhammad Zahir Hassan, 2012. A parallel study of vibration analysis and acoustic analysis in low frequency brake noise *4th INTERNATIONAL CONFERENCE ON NOISE, VIBRATION AND COMFORT (NVC) 2012*. . 26<sup>th</sup> - 29<sup>th</sup> November. Kuala Lumpur, Malaysia.

## **CHAPTER ONE**

### **INTRODUCTION**

#### **1.1 Introduction**

Disc brake noise is a major issue in the current automotive industry. Investment in efforts and cost is still a major expenditure despite recent developments in the race to reduce the noise and vibration in the automotive brake system (Akay, 2002). The brake systems have been subjected to experiments and modeling since the invention of the disc brake system. Recent development in vehicle noise, vibration and harshness (NVH) has made the passenger vehicle operate in a quieter manner thus making the brake vibration to become the center of research focus.

Eliminating the low frequency brake vibration receives serious attention from car makers as it causes discomfort to the passengers inside the vehicle. Brake vibrations rarely compromise the performance of braking but it is subjected to warranty claims and customer complaints as the vibration is related with the quality of brake system (Akay, 2002).

The understanding of the vibration phenomena and the effort to control the brake vibration is a continuous challenge in the automotive braking industry. Generally the brake vibration is perceived as a friction-induced forced vibration (Rhee *et al.*, 1989). The characteristics of a braking event are complicated as the input to the brake system varies with



unlimited number of combinations and the brake assembly itself is a set of multiple components connected with complex interfaces.

The brake vibration is categorized into two categories based on its occurring frequencies. One is the low frequency domain which is the vibrations below the 1 kHz, and the other is the high frequency domains which are the vibration above 1 kHz. Vibration types such as groan, moan, hum and judder falls in the low frequency domain where else the high frequency domain contains the squeal type noise (Jacobsson, 2003). The low frequency noise types are generally caused by brake pad excited by the brake rotor at the contact and it is coupled with other vehicle components (Dunlap *et al.*, 1999). Where else the squeal noise is said to be a friction induced vibration combined with thermal and structural effects. (Hassan, 2007)

## **1.2 Problem Statement**

For the study of the mechanisms which produced the noise types in the low frequency domain the analytical method is suitable as the analytical model simulates the motion of the brake components relative to each other. The properties of the components can be altered in ease to deduce the response vibration. Achieving this experimentally involves high cost and increases the development process (Yumoto and Okamura, 2006).

The low frequency brake vibrations mentioned earlier are well studied and the analytical models were developed to explain the mechanisms behind each vibration types. Mainly these studies revolve around the stick and slip mechanism, mode couplings and dynamic system instability (Ammar *et al*, 2011, Hetzler and Seemann, 2006, Sinou and